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Advanced, Waveform Based Acoustic Emission Detection of Matrix Cracking in Composites

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Abstract

An advanced, waveform based acoustic emission (AE) system was used to study the initiation of transverse matrix cracking in cross-ply graphite/epoxy (gr/ep) composites. The AE signals were detected with broad band, high fidelity sensors, and digitized for analysis. Plate wave propagation analysis was used to discriminate noise signals from those generated by cracks. The noise signals were confirmed to have originated in the specimen grip region by a new, highly accurate form of location analysis which was independent of threshold setting. Six different specimen thicknesses ($[0_n, 90_n, 0_n]$, n = 1 to 6) were tested under stroke controlled, quasi-static tensile loading. The presence and location of the cracks were confirmed post test by microscopy. Back scatter ultrasonics, penetrant enhanced X-ray techniques, and in limited cases, destructive sectioning and microscopy were also used to determine the length of the cracks. For thicker specimens ($n > 2$), there was an exact, one to one correspondence between AE crack signals and observed cracks. The length of the cracks in these specimens extended the full specimen width. Precise linear location of the crack position was demonstrated. The average absolute value of the difference between the microscopy determined crack location and the AE crack location was 3.2 mm. for a nominal sensor gage length of 152 mm. A four sensor array was used which not only improved the linear location accuracy, but also provided the lateral position of the crack initiation site. This allowed determination of whether the cracks initiated in the interior bulk of the specimens or along the free edges. For all cracks, the location of the crack initiation site was at one of the edges of the specimen. The cracks were more difficult to detect with AE in the thin specimens ($n \leq 2$). The cracks in these specimens also initiated at the specimen edge, but did not immediately propagate across the specimen width. They generated significantly smaller amplitude AE signals. These measurements demonstrated that the same source mechanism can generate a wide range of AE signal amplitudes.

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Introduction

An advanced, high capture rate, waveform based AE system was used to study transverse matrix crack initiation in cross-ply gr/ep coupons. Transverse matrix cracking was chosen for evaluation of the improved location accuracy and enhanced noise discrimination capabilities of this new AE system because matrix cracking has been, and remains, a subject of considerable interest and importance. A vast amount of literature on the experimental detection of matrix cracks is available, of which, a small sampling [1-27] is discussed in this paper.

In this study, a unique four AE sensor arrangement was applied on these narrow (2.54 cm.) coupons instead of one or two sensors as typically used in the past [14-25]. This sensor configuration yielded not only improved accuracy in the linear location of the crack position, but also provided, for the first time, a direct measurement that transverse matrix cracks initiated at the specimen edge rather than within the interior of the specimen. This result is of significant importance in examining the validity of extrapolating laminate strength data from coupons to structures which do not have similar free edge characteristics.

Broad band, high fidelity sensors were used to measure the surface displacements caused by the AE wave motion. Accurate waveform measurements allowed for analysis based on plate wave propagation effects which have been previously reported [24, 28-36]. Plate wave analysis permitted the discrimination of signals produced by cracks from signals created by noise sources. These noise signals were confirmed to have originated in the grip region by a new, highly accurate source location analysis technique that is independent of threshold setting. This noise signal elimination was possible even without the use of grip tabs which are commonly used to reduce such noise signals.

The high capture rate feature of the instrument gave improved results as compared to a recent similar study [24-25] which used low capture rate waveform digitization with a digital oscilloscope. In this previous study, only a subset of all crack signals were digitized and analyzed, and only a single cross-ply laminate was studied. However, it did establish a physical model justifying the plate mode characteristics observed in matrix crack AE signals and illustrated the phenomenon with simulated AE sources (pencil lead breaks at different orientations with respect to the plate). In this work, all detected crack signals were recorded. Combined with the noise discrimination capability, this allowed for an exact, one-to-one correlation between AE crack signals and actual cracks in specimens with thick 90 degree layers (greater than two ply thicknesses) where the cracks immediately grew across the width of the specimen. The cracks were confirmed after testing with other techniques including microscopy, backscatter ultrasonics and radiography.

For specimens with thin 90 degree layers, much smaller amplitude AE signals were observed which were difficult to consistently detect. A good correlation between the AE data and observed cracks was not established. Through the use of backscatter ultrasonics, destructive sectioning and microscopy, it was discovered that the cracks did not appreciably grow from the edge after initiation in specimens with a 90 degree layer of two or less ply thicknesses. This limited crack growth behavior was attributed as the reason for the significantly reduced amplitude AE signals. In a previous study [19-20] which used a conventional AE system and amplitude distribution analysis, similar thickness effects on signal amplitudes were reported, but not explained. For samples with thick 90 degree layers (again, greater than two ply thicknesses), there was a near one-to-one correlation between high amplitude AE signals and observed cracks with good separation between the peak in large amplitude signals and the peak containing numerous smaller amplitude events. However, no attempt was made to use location analysis of the AE data for further confirmation that the high amplitude signals were indeed caused by cracks. For specimen with a 90 degree layer thickness of two plies, there was a poor correlation between high amplitude signals and observed cracks. The motivation for testing specimens of different 90 degree layer thickness is that other studies [1-4] using radiography and microscopy have suggested that the stress required to initiate cracking is a function of the thickness of the 90 degree layer in a cross-ply composite. As the thickness of this layer decreases, the first ply failure stress increases. These results point out the need for further study, and the development of improved sensitivity transducers for use on laminates with thin 90 degree layers. Such layups are more representative of materials used in real structures.

An extremely important outcome of these tests is the observation that the same source mechanism in a composite, transverse matrix cracking, produced a wide range of signal amplitudes. The signal amplitudes depended on the 90 degree layer thickness. They also depended on the length of propagation of the crack across the width of the specimen. The waveforms also showed that dispersion and attenuation significantly altered the amplitude of signals even for the short distances of propagation within the same specimen. The literature is already full of conflicting results concerning AE amplitudes and source mechanisms. Some studies, for example

[14-16], reported that matrix cracking produced acoustic signals of low amplitudes while delamination and fiber breakage produced signals of higher amplitudes. Others [17-20], however, claimed that matrix cracking was the source of high amplitude events. Still others [22-23] stated that signals from different source mechanisms could not be distinguished by amplitude alone. To make matters more confusing, most of these studies do not have direct confirmation of the source mechanisms to compare with the AE data. The source mechanisms are assumed based on the type of damage expected in the given laminate structure. Fracture energy considerations have been used in attempts to explain why a given source mechanism might produce larger or smaller amplitude acoustic signals, but the arguments have not been convincing. Also, the effects of wave propagation, such as attenuation, dispersion, and multiple modes of propagation have been largely ignored. One exception [21] discussed the significant effects that attenuation can have on these measurements and how they could be a cause for some of the discrepancies reported in the literature.

Transverse matrix cracking is of such interest and importance because it is the first mode of damage that occurs in cross-ply composite laminates under load testing. These cracks cause stiffness degradation which can be the lifetime limiting damage mechanism in stiffness dependent aero-space applications and they may lead to the initiation of delaminations. A number of other experimental techniques have been used to detect matrix cracking. Visual methods work in some translucent materials such as fiberglass. However, gr/ep is opaque. Penetrant enhanced radiography [3-9, 14, 17, 19, 20], microscopy [5, 7, 11], and edge replication [6, 10] are the most commonly used techniques for this material. However, these techniques suffer from the fact that the load test must be interrupted periodically which limits the load resolution that can be obtained, particularly when multiple cracks occur within a given load increment. The time involved is significant, so a trade-off exists between the desired load resolution and the number of test pauses. Furthermore, the specimen is often unloaded and removed from the test machine for each measurement which further adds to the time required to complete a test. Removing the specimen may induce artifacts in the results due to alignment problems in regripping the specimen and the step-wise loading procedure may influence the mechanical behavior of the specimen due to low cycle fatigue effects [8]. Also, one study [10] has demonstrated that solvents used in edge replication may lead to premature cracking of the matrix.

Another technique that has been used to study transverse matrix cracking is backscatter ultrasonics [25, 27]. This technique suffers from similar limitations to those discussed above in that the loading must be interrupted, the specimen removed from the machine and scanned. The specimen must then be replaced in the load frame. Another limitation is the difficulty in resolving two or more closely spaced cracks. However, backscatter ultrasonics can provide information about the lateral extent of the crack whereas microscopy and edge replication do not, and it may be possible to develop the technique whereby the specimen can be scanned in situ.

One technique that has overcome some of these difficulties is the use of a piezoelectric load cell. This allows for in situ continuous monitoring for cracks. However, the technique is limited to laminates with a four ply or thicker inner 90 degree layer because of background noise problems [19]. Also, in an attempt to monitor continuously in situ, a more recent study [26] attempted to detect transverse matrix cracks with audible frequency microphones placed near the specimen. However, acoustic signals from cracks could not be clearly differentiated from other noise sources such as grip induced damage, specimen slippage, or test machine noise.

As demonstrated in this research, advanced AE instruments and techniques can be employed to monitor transverse matrix cracking in situ during load testing. The improved AE methods can provide highly accurate linear location of the crack positions, as well as information about the crack initiation site and the crack growth behavior. High resolution in determination of the loads required to initiate cracking can be obtained. This can all be accomplished without influencing the specimen behavior and thus the measured results.

Theory

It has been documented [24, 28-36] that AE signals in thin plates and plate-like geometries such as shells and pipes, propagate as the lowest order symmetric (S_0) and antisymmetric (A_0) Lamb modes. For thin plates and low frequencies (i.e. when the wavelength is large with respect to the plate thickness), the propagation characteristics of these waves can be adequately described by approximate plate theories such as classical plate theory and Mindlin plate theory. These theories yield much more simple equations from which to predict dispersion relations than the transcendental Lamb equations. They can also be used to predict the flexural mode wave shape in finite plates [35]. The details of these theoretical approaches are beyond the scope of this paper but are presented in many of the above mentioned references.

Adopting plate theory terminology, the S_0 mode is referred to as the extensional plate mode and the A_0 mode is denoted the flexural plate mode. The extensional mode propagates with a faster velocity and for thin plates suffers little dispersion over the frequency range observed in most AE experiments (20 kHz to 1 MHz). It typically contains higher frequency components than the flexural mode. The predominant particle displacement for the extensional mode is in the plane of the plate. The flexural mode, however, propagates with a slower velocity and is highly dispersive with the higher frequencies traveling at higher velocities. The largest component of its particle displacement is out of the plane of the plate. A typical waveform detected with a broad band sensor identifying these two modes is shown in Fig. 1. The source of this signal was a simulated AE event caused by a pencil lead fracture (Hsu-Neilsen source) on the surface of the plate.

Two aspects of plate wave propagation have been shown to be particularly important for AE analysis. The first is the effect of the direction of source motion on the relative amplitudes of these two plate modes [28-30]. For source motion perpendicular to the plane of the plate or asymmetric with respect to the midplane of the plate, the flexural mode is predominant in the observed AE signal. Examples of sources which have this characteristic include particle impact on a plate or delamination of a composite laminate. This source motion can be easily simulated by breaking a pencil lead on the surface of the plate as shown in Fig. 1 where the flexural plate mode has a much larger amplitude than that of the extensional mode. Noise signals from grip damage, which occurs on the surface of the specimen, also produce large flexural mode signals in tensile tests. When the source motion is in the plane of the plate and symmetric about the midplane, the extensional mode component has a larger amplitude. Such a source motion is representative of in-plane matrix cracking in a composite laminate or tensile fatigue cracking in aluminum. This motion can be simulated by fracturing a pencil lead on a free edge of the plate along the midplane. A typical signal from such a simulated source is shown in Fig. 2. Comparison with Fig. 1 shows the difference in amplitudes of the two plate modes. An alternative method for simulating this source motion when a free edge of the specimen is not available has also been described [37]. The effect of source motion on the relative amplitudes of the plate modes has been used to differentiate in-plane cracking from grip related acoustic noise in static and fatigue tests of composites and metals [24-25, 31-32]. In these studies, low capture rate digital acquisition (digital storage oscilloscopes) were used to demonstrate this phenomenon. This type of instrumentation is inadequate for the large numbers of signals detected in practical AE tests. However, high capture rate, digital waveform systems overcome this limitation and readily allow this type of analysis to be performed.

Conventional AE analysis techniques are limited to signal parameter correlations which have sometimes been used successfully to discriminate noise signals. Most often, event duration is the parameter used. However, these correlations are usually not based on scientific understanding, but on empirical observations. Waveform analysis based on the physics of wave propagation may in some cases explain such correlations and their limitations.

The second important aspect of plate wave propagation on AE analysis is the existence of multiple modes which propagate with different and dispersive velocities. This has been demonstrated to have a significant effect on the location accuracy of AE systems, particularly when the arrival time is determined from the first threshold crossing time [33]. This effect is demonstrated in Fig. 3 where waveforms from the same source but at different distances of propagation are shown. In this figure, three different thresholds are illustrated. The lowest threshold would provide reasonable location accuracy based on the extensional mode velocity since the extensional mode crosses the threshold in both cases. The intermediate threshold would provide inaccurate results since it determines an arrival time based on the extensional mode for one signal and the flexural mode on the other signal. The third and highest threshold detects the same flexural mode for both signals, but at different frequency components which would also yield inaccurate results. This is a another area where digitization and analysis of the AE signals can provide a significant improvement over conventional parameter based systems which all use first threshold crossing methods. The digitized waveforms can be analyzed in more detail to measure identical phase points within the same wave mode which will yield much more precise location results. Matching phase points can either be done manually with a cursor as was done in this study, or with cross correlation techniques [33].

Experiment

Tensile coupon specimens (2.54 cm. wide by 27.94 cm. long) of AS4/3502 graphite/epoxy composite material were tested under stroke control loading (0.127 mm/minute). Specimen end tabs which are often used in AE tests to reduce noise signals created by grip damage, were not used in these tests. Grip noise was eliminated by waveform analysis. Specimens from six different cross-ply laminates were tested. The stacking sequences were $[0_n, 90_n, 0_n]$ where n ranged from one to six. Thus, the samples varied in thickness from 3 to 18 plies. The specimen for n = 5 and 6 had a small number of preexisting cracks (three or less) that had been caused by residual thermal stress effects during curing. However, these existing cracks were in the specimen grip region and outside the gage length.

Broadband, high fidelity sensors (Digital Wave Corporation B1000) were used to detect the waveforms. These sensors produce a flat frequency response from below 100 kHz to above 1 MHz. Below 100 kHz, the response of these sensors falls off gradually with adequate sensitivity provided to below 50 kHz. Rather than a single sensor at either end of the specimen as in works previously cited, four sensors were used. At either end of the nominally 152 mm. specimen gage length, a pair of sensors were positioned. The outer edge of each 6.35 mm diameter sensor was aligned with the edge of the specimen. A diagram of a specimen showing the sensor positions and the grip regions is shown in Fig. 4. The motivation for this sensor array arrangement was the determination of the initiation site of the crack. Not only could the linear location along the length of the specimen be determined, but lateral location information was also obtained. The maximum digitization sampling frequency (25 MHz) of the digital AE acquisition and analysis system (Digital Wave F4000) was used to provide the most accurate location results. Location was performed, post-test, using manual, cursor based phase point matching on the extensional mode for arrival time determination. The extensional mode velocities used for the location analysis were measured prior to testing using simulated AE sources (pencil lead breaks on the edge of the specimen).

After detection, the signals were amplified 20 dB by wide band preamps (Digital Wave PA2040G). It was determined during the tests that the signal amplitudes were a function of the 90 degree layer thickness, so additional system gain was varied to maintain the signal within the dynamic range of the 8 bit vertical resolution of the digitizer. Thicker specimens generated signals of larger amplitude. The additional system gain ranged from as little as 6 dB for the thickest specimen to 18 dB for the nine ply specimen ($n = 3$). For the three and six ply laminates ($n = 1$ and 2), the signal amplitudes were significantly smaller as will be discussed below. For these, the preamp gain was increased to 40 dB and the system gain was set as high as 18 dB in attempts to capture the much smaller amplitude signals. The load at which a given crack signal was detected was obtained from a parametric measurement system in the AE instrument.

After observation of one or more transverse matrix crack AE signals, the load test was stopped and the specimen removed from the test machine. One edge of the specimen, which had been polished prior to testing, was examined under an optical microscope. The specimen was mounted on an x-y translation stage to allow measurement of crack locations for comparison with the AE data. Backscatter ultrasonic scans were taken to further confirm the crack locations and to provide information about the lateral extent of the cracks. This method also confirmed that no cracks existed which were not detected at the one polished edge. In some cases, penetrant enhanced radiography was also used as was destructive sectioning and microscopy.

Extraneous noise signals were eliminated by post test analysis of the waveforms. Typical waveforms from both a crack source and a noise source are shown in Fig. 5. Because of the multiple reflections of the signals across the narrow width of the coupon specimen, the signals are more complicated than those presented in Fig. 1 and 2 which were detected in a large plate. However, the high frequency extensional mode is clear in the crack signal. A small extensional mode component is observed in the noise signal followed by a much larger, low frequency, dispersive flexural mode signal. The source of the noise signals is believed to be grip damage or specimen slippage in the grips as all of the noise signals located outside the specimen gage length in one of the grip regions. Only a few noise signals were observed throughout the testing, with a number of specimens producing none. Typically the noise signals occurred at lower loads before the matrix cracks were detected. Another interesting observation was that an audible pop was often heard simultaneously with the detection of a noise signal while the matrix cracks were not audible. This was most likely due to the lower frequency components of the flexural mode and its larger out of plane motion. This explains why microphone detection of matrix cracking proved difficult [26].

Results

For the laminates with n = 3 or larger, there was an exact one-to-one correlation between the AE crack type signals detected and cracks confirmed with microscopy and ultrasonics. A micrograph of a typical transverse matrix crack is shown in Fig. 6 along with a backscatter ultrasonic scan of a region showing multiple cracks. For all cracks, backscatter ultrasonics indicated that the cracks extended across the full width of the specimen and that none were present which were not observed by microscopy of the polished edge. Destructive sectioning and microscopy of a few of these cracks also confirmed this result. The fact that only a single AE signal was detected for each crack indicates that the cracks immediately propagate across the width of the specimen. The amplitudes of the signals were proportional to the thickness of the 90 degree layer, with thicker layers producing larger amplitude signals.

Excellent crack location accuracy along the length of the specimens was obtained from the

AE data as compared to microscopy measurements. As will be discussed below, all cracks originated along one or the other edges of the specimens. The most accurate linear location was obtained by using the two sensors on the same edge as the crack initiation site. The pair of sensors on the opposite edge produced much more inaccurate locations because of several effects. First, the direct waves travelled an increased distance crossing the width of the specimen. Also, the velocity of the waves travelling at angles across the specimen is different (slower) than the signals propagating directly along the specimen edge. Finally, the increased distance of propagation and the more attenuating direction of propagation contributed to reduce the amplitude making arrival time determination more difficult. These effects would also affect location measurements made from transducers mounted in the center of the specimen width as is most commonly used. Using the results from the sensors on the same edge as the crack initiation site, the average of the absolute value of the difference in crack locations from AE and microscopy was 3.2 mm for a nominal sensor gage length of 152 mm. Typically, the cracks located toward the center of the gage length were more accurately located with AE while those closer toward one end of the specimen showed larger errors. This is to be expected as the signals are more equally affected by attenuation and dispersion when the distance of propagation is nearly the same which occurs for cracks near the center of the gage length. Fig. 7 shows the location results as compared to microscopy locations for a specimen that was loaded until nine cracks within the gage length were detected.

For these thicker specimens, location analysis of the four sensor array data indicated that all cracks initiated along one or the other specimen edge. A typical four channel set of waveforms from a matrix crack signal is shown in Fig. 8 along with a diagram indicating the sensor positions and the crack location. These signals clearly show the time delay between the pairs associated with the crack initiation site being located along the edge. Furthermore, differences in amplitudes between the sensors within a pair indicate the increased attenuation across the specimen. The differences in signal amplitudes and frequency content for signals detected at opposite ends of the specimen and thus different distances of propagation distances should also be noted. These differences, which are caused by attenuation and dispersion, can have significant effects on location accuracy and conventional amplitude distribution analysis. Another interesting observation in these tests was that only 30 percent of the crack signals initiated along the edge that was polished prior to testing. Thus, the majority initiated on the unpolished, rougher specimen edge which may indicate that micro-damage sites along the edge may serve as stress concentrations from which the cracks initiate. This indicates that surface preparation may have an influence on the stress measured to initiate cracking.

The following table shows values for loads for first transverse matrix crack initiation versus laminate stacking sequence for one set of specimens. Preliminary analysis of this data for all

Stacking Sequence	Load for first crack (lbs.)
$[0_6, 90_6, 0_6]$	5688
$[0_5, 90_5, 0_5]$	4153
$[0_4, 90_4, 0_4]$	3594
$[0_3, 90_3, 0_3]$	3220

thicker specimens tested are in agreement with the 90 degree layer thickness effect on crack initiation stress previously reported [1-4]**.** Further application of this data to study the mechanical models to predict this effect is underway.

For the thin laminates (n = 1 or 2), the AE signals from cracks were not always successfully detected and the signals detected were significantly smaller in amplitude. Ultrasonic backscatter scans and destructive sectioning microscopy analysis showed that the cracks, which were visible at the specimen edge, did not extend into the interior of the specimen. Thus, the cracks were again initiating along the edge, but not progressing immediately across the specimen. This difference in crack initiation and growth behavior explains the much smaller amplitude signals and the difficulty in detecting these cracks. This result may also explain an earlier study of similar specimens [19, 20] in which conventional analysis of AE amplitudes was used. For specimens with thick layers of 90 degree plies, there was a near one-to-one correlation between the high amplitude events and the cracks observed with radiography. However, for specimen with thin 90 degree layers, high amplitude events did not correlate with observed cracks.

Conclusions

This study produced a number of important results for the understanding of both the analysis of acoustic emission signals in composites as well as the crack initiation and growth behavior of different thickness cross-ply composite laminates. The major findings are summarized below.

1. An identical source mechanism, transverse matrix cracking, can produce a wide range of AE signal amplitudes. The thickness of the layer in which the crack occurs and the distance the crack propagates significantly affect the observed amplitude. Furthermore, the detected amplitude is fur-

ther influenced by dispersion and attenuation based on the distance that the signal propagates. Thus, attempts to differentiate matrix cracking from other source mechanisms in composites by conventional amplitude analysis alone should be undertaken with extreme care.

2. For all specimens, transverse matrix cracks initiated along one of the specimen edges. However, crack initiation and propagation behavior was a function of the 90 degree layer thickness. For thick layers, the cracks immediately propagated across the specimen width. For thin layers, the cracks initiated at the specimen edge but did not progress further across the width at the low loads of the test. Preparation of the specimen edges also seemed to influence the initiation of cracking for the thicker specimen.

3. Plate wave propagation analysis, made possible by the use of broad band sensors and waveform digitization, allowed separation on crack signals from noise signals created in the grip region. Previous studies demonstrating that cracks signals produce extensional plate mode signals were confirmed. This allowed an exact one-to-one correlation between AE detected cracks and cracks confirmed with microscopy and backscatter ultrasonics. Accurate source location results were also demonstrated.

Future research will focus on measurement of the progression of transverse matrix cracking until specimen failure in the thick laminates. Further attempts will also be made to consistently detect the initiation of cracking in the thin laminates.

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Figure 1 - Typical plate wave signal created by lead break on surface of a gr/ep composite plate showing extensional and flexural modes.

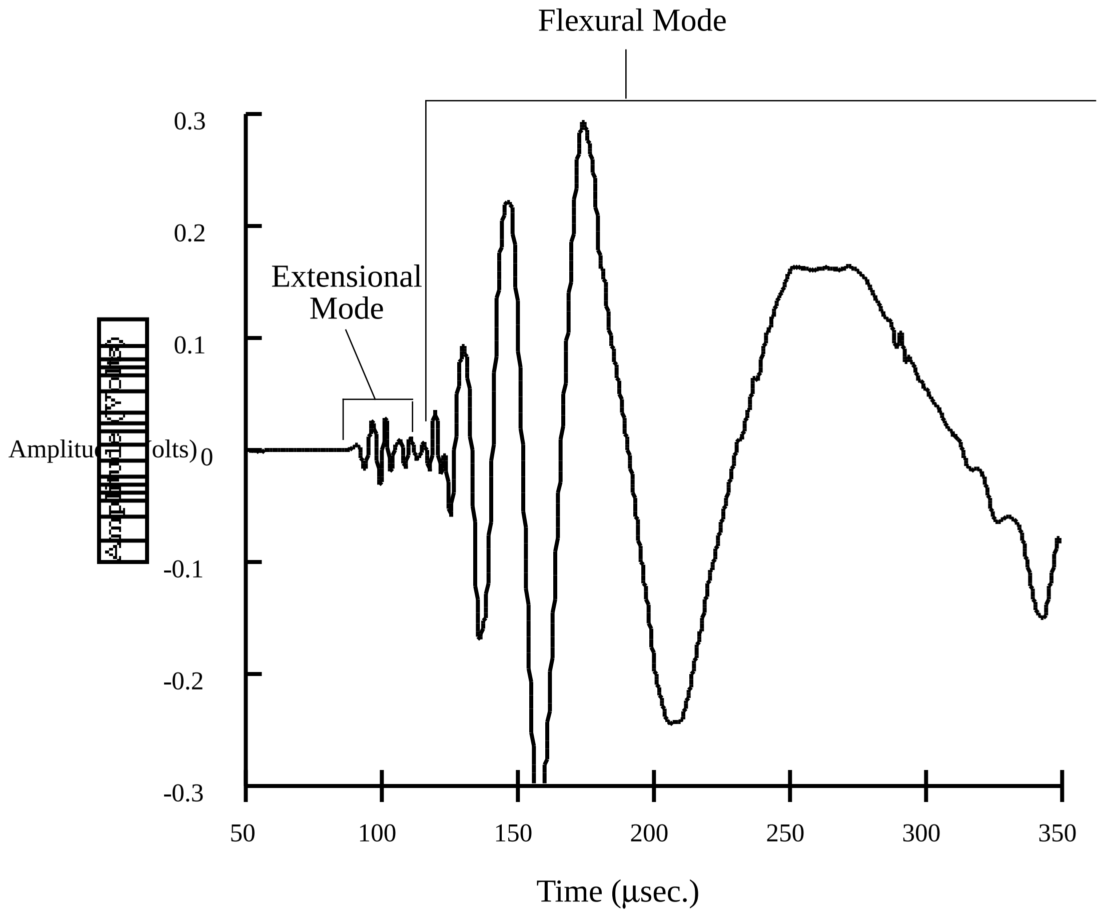


Figure 2 - Typical plate wave signal created by lead break on edge of gr/ep composite plate.

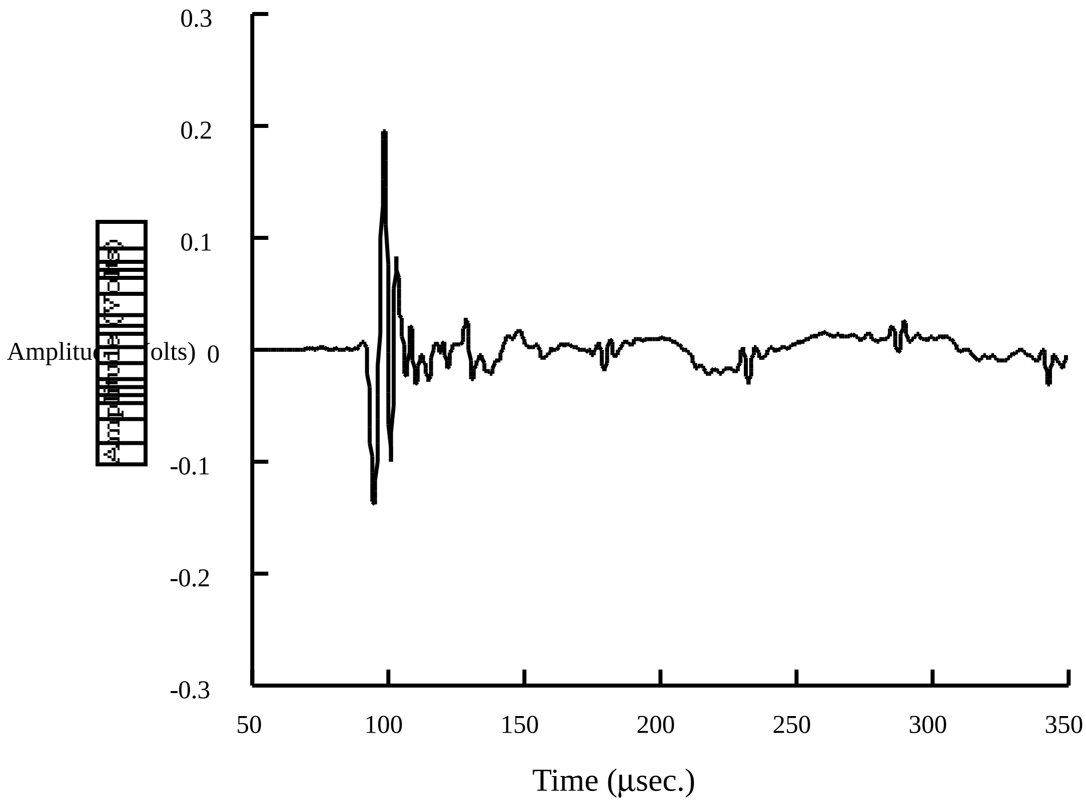


Figure 3 - Simulated AE signals at different source to receiver distances demonstrating the effect of threshold (TH) setting on arrival time determination for three different threshold values.

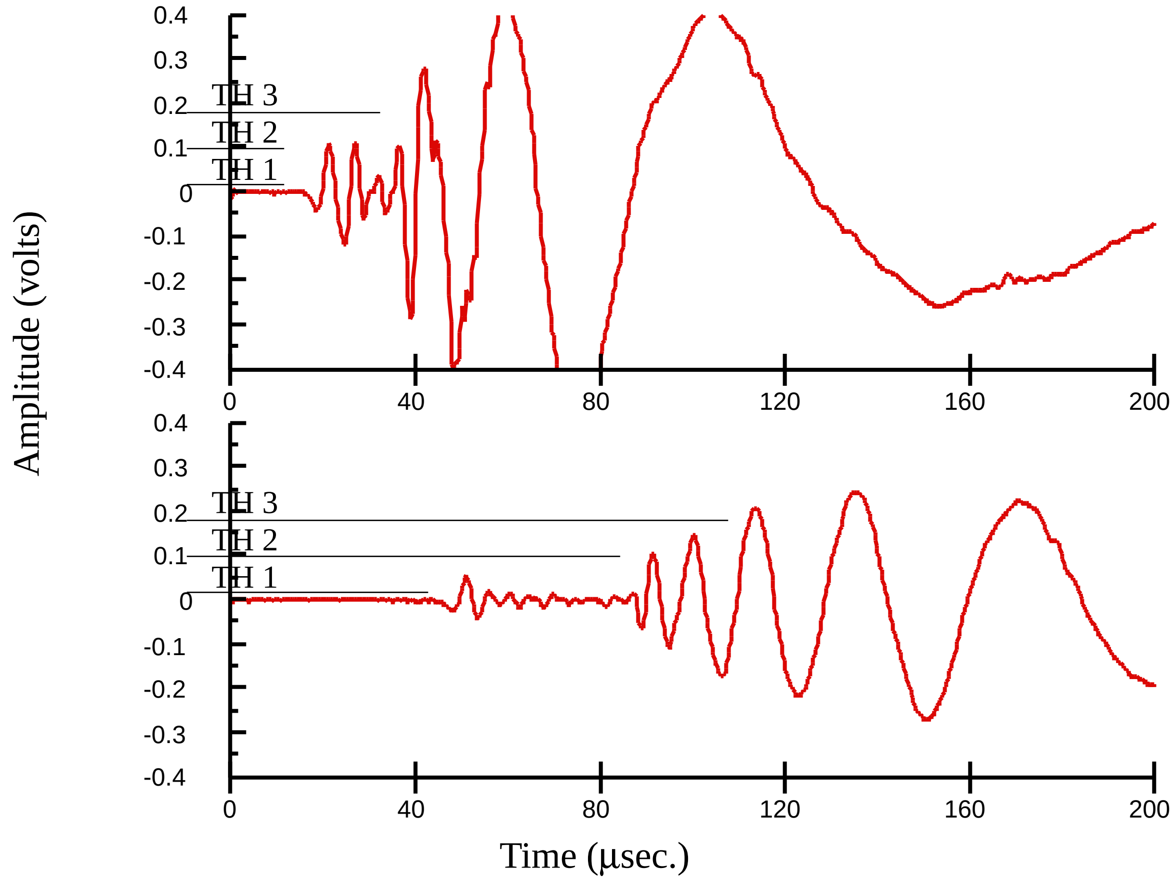


Figure 4 - Diagram of specimen showing grip region and position of AE sensors.

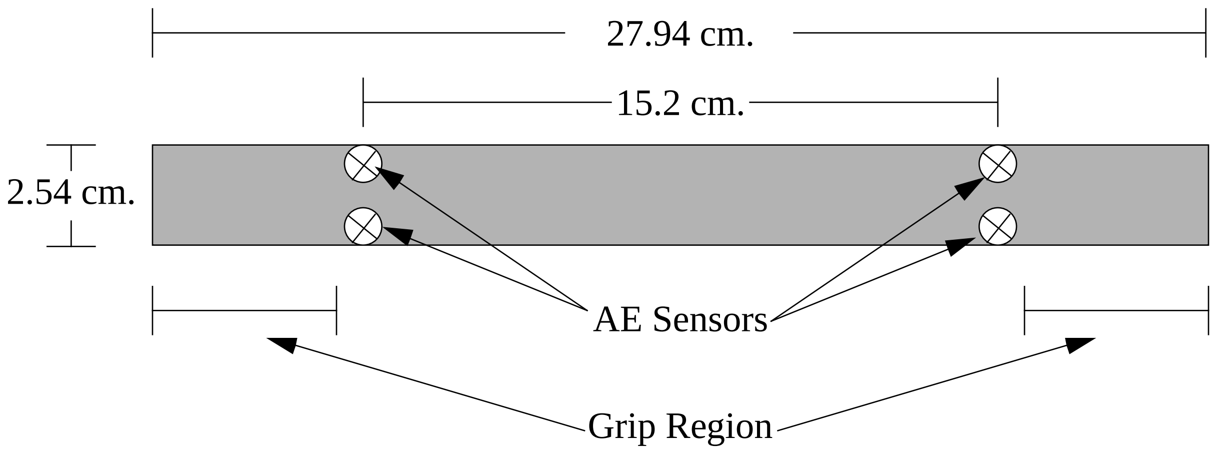
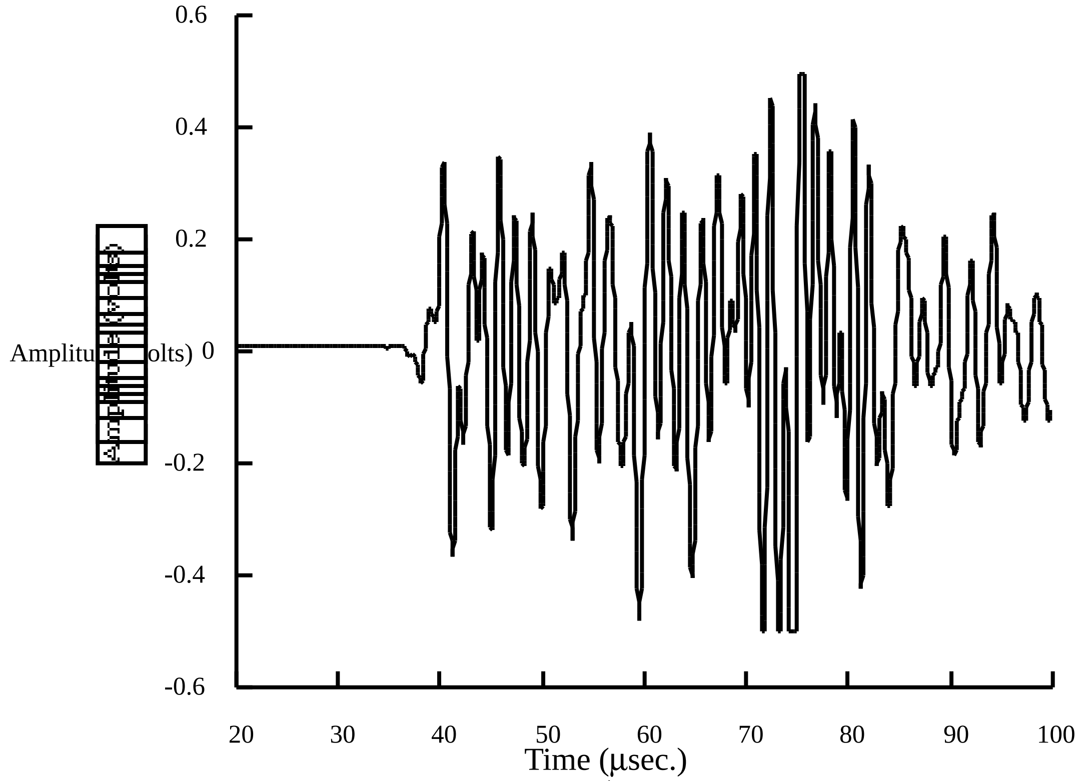
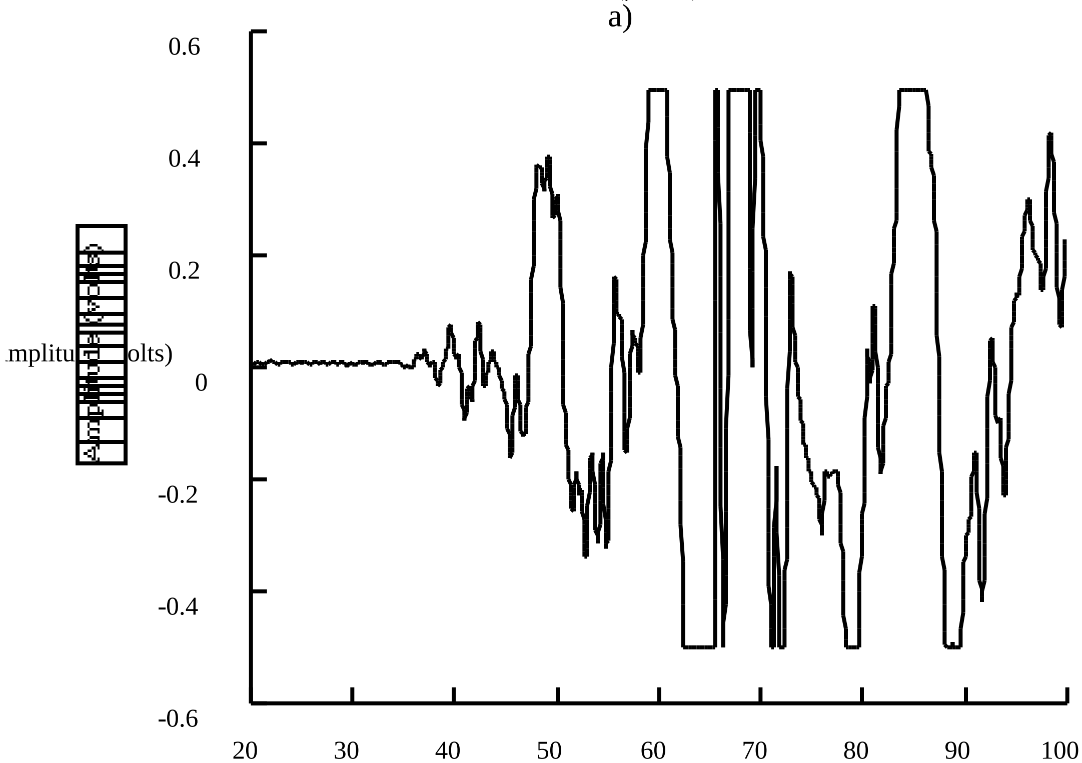


Figure 5 - Typical signals from a) transverse matrix crack source and b) noise source.

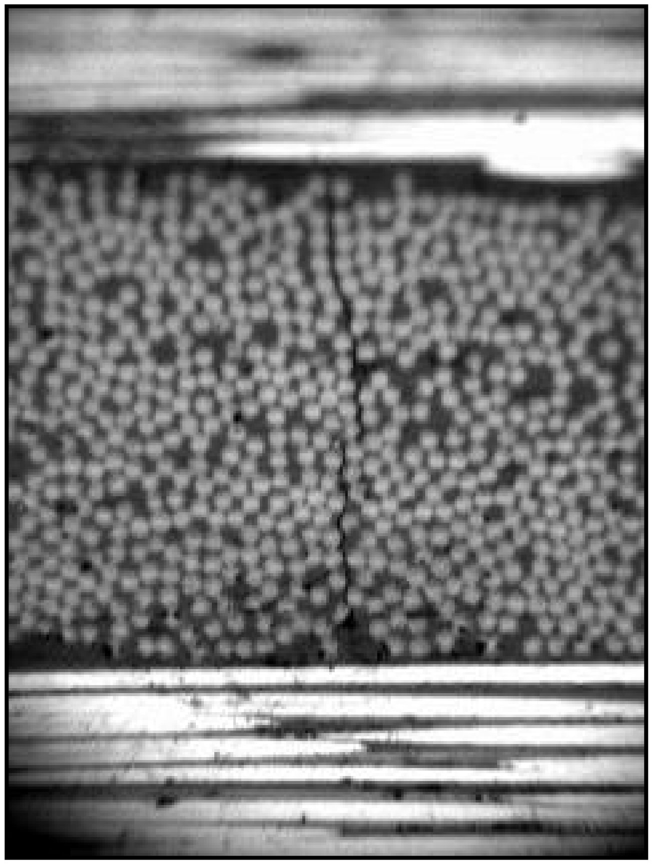


a)

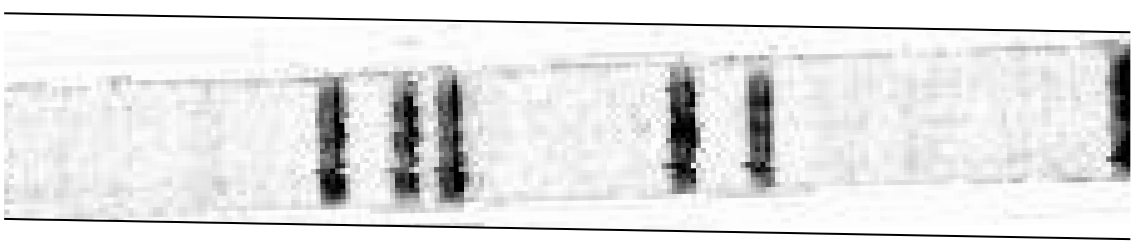


b)

Figure 6 - a) Micrograph of typical matrix crack and b) backscatter ultrasonic scan showing multiple transverse matrix cracks.



a)



b)

Figure 7 - Location results for a specimen loaded until nine cracks were detected.

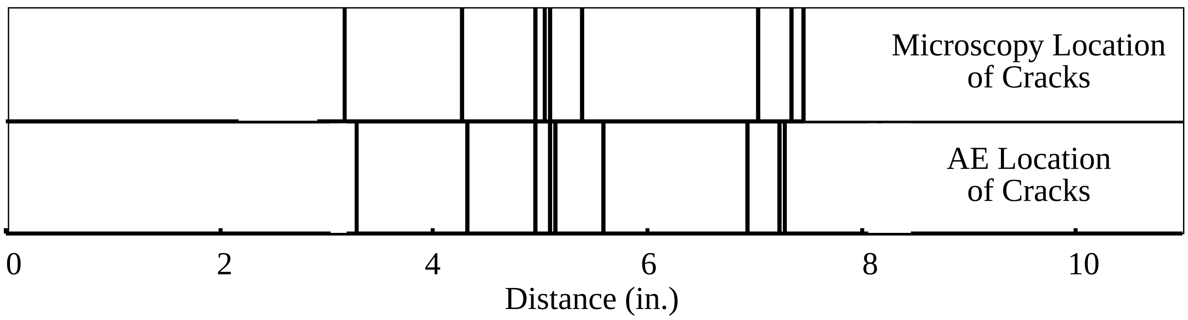
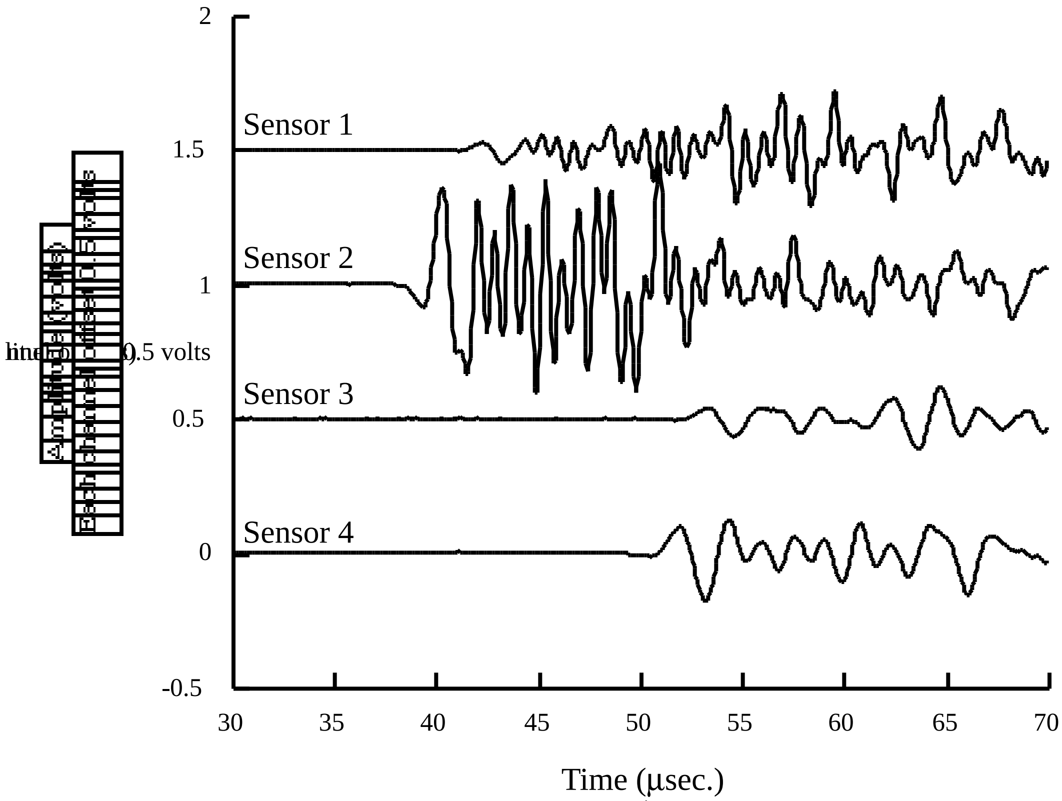
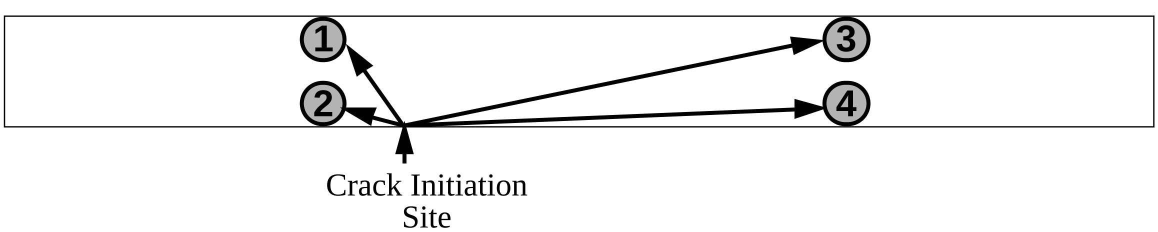


Figure 8 - a) Set of four channel waveforms indicating crack initiation along the specimen edge and b) diagram showing sensor positions, crack initiation site, and rays of direct propagation for the AE signal.



a)



b)